FORCE-LENGTH PROPERTIES OF LEG EXTENSION AND THEIR IMPLICATIONS FOR STRENGTH DIAGNOSTICS

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The aim of this study was to identify the *F-l-r* of multiarticular leg extension and its relation to muscle function. For that purpose, external forces and kinematics of lower extremity were measured (*n = 18*) during maximum voluntary isometric contractions in a seated leg press. Range of Motion was 30° - 100° knee flexion and measurements were done in steps of 10°. In addition, net joint moments for hip, knee, and ankle joint were computed by inverse-dynamic modelling. With increasing knee flexion one-legged maximal external force (F_{ext}) decreased significantly from 3369±575 N to 1015±152 N, whereas passive forces only had a minor influence. Moreover, correlations showed that above average F_{ext} at low knee flexion is not necessarily associated with above-average F_{ext} at great knee flexion and vice versa. Similarly, it is not possible to simply deduce high joint moments for all joints from high F_{ext}, just as above-average joint moments in one joint don't implicitly signify above-average joint moments in another joint. In conclusion, these results show that the diagnosis and interpretation of leg extension strength in terms of muscle function via external forces must be done with extreme caution.

KEY WORDS: force-length relation; leg extension; muscle function; strength diagnostics

INTRODUCTION:

In many respects, the force-length relationship (*F-l-r*) is an important property of skeletal muscle. Especially for sports activities, force-length properties may affect performance (Herzog et al. 2003) and maximum isometric strength is an important parameter of diagnostics for training control. However, as the well known *F-l-r* (Edman et al. 1987, Gordon et al. 1966) results from isolated muscle preparations and supramaximal activation, it does not necessarily reflect *in vivo* human muscle function. Alternative approaches that have been used for the estimation of *in vivo* force-length properties are human strength curves (Kuhlig et al. 1984) as well as more sophisticated methods (Herzog et al. 1988, Maganaris 2001), but mostly all studies that used one of these approaches (e.g. Anderson et al. 2007) are restricted to single-joint movements. Although single-joint tests provide helpful information on specific strength of a muscle or muscle group, the problem arises that they appear to be much less useful in reflecting performance capabilities on multiple-joint activities (Weiss 2000). On the other hand, due to the complexity of the lower extremity multilink system, external forces are not directly related to joint moments and muscle forces (Zatsiorsky 2003), so that an evaluation of muscle function based on external forces remains difficult.
Regarding force-length properties of multiarticular leg extension, to our knowledge there is only data on external forces (Berger 1966, Hugh-Jones 1947, Lindenburg 1964), since the studies that used modelling approaches mainly dealt with dynamic rehabilitation exercises (e.g. Toutoungi et al. 2000, Zheng et al. 1998). Thus, the aim of this study was to determine the *F-l-r* of multiarticular leg extension, whereas the evaluation of muscle function was not only based on external forces but also on joint moments calculated by inverse dynamics.

METHOD:

Data Collection: Moderately active male subjects (*n* = 18; 30 ± 6.3 years of age) without any neuromuscular disorders or injuries at the lower extremity participated in this study. Experiments were carried out in a leg press dynamometer (IsoMed2000, D&R FERSTL GMBH, Germany), whereas individual measurement positions for the investigation of force-length properties were calculated according to an anthropometric standardisation model (Hahn et al. 2005). External reaction forces exerted on the leg press were measured separately for each leg by a custom build force plate with 3-component force sensors

(KISTLER, Switzerland). Based on the markerset of the Newington-Helen Hayes Model (Charlton et al. 2004) a VICON MX-3 Motion-System (USA) served for measuring lower extremity kinematics. Capturing frequency and sampling rate for analog data was 240 Hz. Kinematic measurements and force recordings were synchronised by software.
Joint moments in hip, knee, and ankle joint were calculated by the methods of inverse dynamics. To account for inertial properties a anthropometrical model was scaled individually to weight and body height by linear regression (Zatsiorsky et al. 1984) and was adjusted according to de Leva (1996).

Experimental protocol: Subjects attended three sessions on 3 different days, with at least 1 rest day between sessions. In two preparation sessions, subjects were familiarized with the test protocol and trained to perform maximal voluntary contractions. The start and end of each contraction was clearly announced to each subject and verbal encouragement was given during the contractions.
The test protocol was split up into three sets. All sets consisted of 8 contractions each at a different knee flexion angle (30, 40, 50, 60, 70, 80, 90, and 100°), whereby 0° knee flexion refers to the straight leg. For each knee angle, subjects had to make 3 repetitions, resulting in 3 sets and a total of 24 contractions. In order to avoid possible learning or sequence effects during the experimental protocol, isometric contractions at different knee angles were presented in a random order in any set. Subjects were given as much rest as required, but a minimum rest of 3 min and 5 min was enforced at all times between contractions and sets, respectively.

Data Analysis: Peak resultant external reaction force (F_{max}) was determined from smoothed force-time histories for each knee flexion angle. Subsequently, corresponding joint moments in hip, knee, and ankle joint were taken at the same instant of time (i.e., at the point of time when F_{max} occurred). Passive forces were obtained 2 s after termination of muscle activation. All data were smoothed by a 4th order Butterworth filter at a cut-off frequency of 7 Hz. Two-way repeated measures ANOVA and Bonferroni-Holm post hoc comparisons served for statistical analysis. Correlations were calculated according to Pearson.

RESULTS:
We found a force-length relationship for multi-joint leg extension with one-legged total external forces decreasing significantly from 3369±575 N to 1015±152 N towards greater knee flexion. All but the forces at 30° and 40° knee flexion showed significant differences, whereas passive forces almost remained constant over the total range of motion. For detailed force-length properties see Table 1.

Table 1: One-legged total and passive external reaction forces subject to knee flexion angle.

	Knee flexion angle [°]							
	30	40	50	60	70	80	90	100
External reaction force (mean) [N]	3369	3239	2748	2236	1750	1385	1157	1015
Standard deviation [N]	575	430	375	322	291	209	180	152
No significance (*p<.05*) to	40°	30°	-	-	-	-	-	-
Passive reaction force (mean) [N]	91.0	79.8	76.9	78.9	69.7	75.5	71.1	72.7
Standard deviation [N]	13.4	18.6	11.3	19.1	22.3	19.0	29.8	16.7
Amount of total external force [%]	2.7	2.5	2.8	3.5	4.0	5.5	6.1	7.2

Further analysis of the force-length data revealed that correlation coefficients decreased with increasing distance between two knee angles. According to this, the force-length relation for multi-joint leg extension could be divided into two parts showing high internal correlations ($r \geq 0.7$): part 1 for knee flexion ≤ 50° and part to for knee angles ≥ 60° knee flexion.
Similarly, the results do not indicate a direct relationship between forces and moments in hip, knee, and ankle joint for all knee flexion angles. According to this, high correlations ($r \geq 0.7$)

between forces and moments were only found when knee flexion exceeded 80° for hip and 60° for knee as well as for the ankle joint, respectively (see Table 2).

Table 2: Correlations between external forces and corresponding joint moments in hip, knee, and ankle joint (level of significance: * *p<.05;* ** *p<.01*).

	External force F at knee flexion angle [°]							
	F30	F40	F50	F60	F70	F80	F90	F100
Correlation to corresponding hip joint moments [*r*]	.278	.239	.519*	.342	.634**	.772**	.777**	.779**
Correlation to corresponding knee joint moments [*r*]	.407	.473*	.668**	.759**	.733**	.702**	.770**	.714**
Correlation to corresponding ankle joint moments [*r*]	.303	.437	.628**	.829**	.845**	.905**	.919**	.871**

Finally, we observed high correlations between knee and hip joint moments, knee and ankle joint moments, and hip and ankle joint moments for knee flexion angles ≥90°, 80°, and 80°, respectively. In contrast, for small knee flexion angles correlation coefficients between joint moments actually became negative.

DISCUSSION:

The purpose of the present study was to investigate force-length properties of multi-joint leg extension to evaluate the underlying muscle function and its implications for strength diagnostics. In comparison to former findings (Berger 1966, Hugh-Jones 1947, Lindenburg 1964) the *F-l-r* described above shows a plateau-region between 30° and 40° knee flexion, whereas others reported a continuous rise before a limiting angle of 20° knee flexion is reached. In addition, in our study forces at great knee flexion were nearly twice as high than postulated earlier. These basic differences might be explained by distinct upper body positions and advantages of the modern leg press device.

New to the literature is the finding that correlations between forces at different knee flexion decreased with increasing distance between the knee angles. According to this, strength abilities of athletes can't be fully described by a single measurement. This is an important result that should attract attention, since the diagnostic of maximum isometric strength is usually limited to a single joint angle.

Another significant result is that external forces are not directly related to hip, knee, and ankle joint moments as theoretically explained by Zatsiorsky (Zatsiorsky 2003). Due to experimental costs, data from strength measurements are typically restricted to external forces so that an evaluation of muscle function must be done with extreme caution. The associated difficulties will be highlighted by two examples. The first example deals with two subjects, which had strongly different leg extension strength at 80° knee flexion (1851 N vs. 1216 N). In spite of that, both subjects realised equal knee joint moments (200 Nm vs. 202 Nm) and the higher external force of subject 1 solely resulted from increased hip and ankle joint moments. Based on these findings a recommendation for subject 2 to strengthen its knee extensor muscles wouldn't be reasonable. In contrast, example two is about two further subjects, who showed similar strength abilities at 60° knee flexion (2582 N vs. 2363 N; 8.4 % difference). However, subjects generated strongly distinct joint moments in the hip (189 Nm vs. 297 Nm) and knee joint (337 Nm, vs. 219 Nm) but equal ankle joint moments. Hence, the latter example finally illustrates the significance of our result that even joint moments of multi-joint leg extension are not directly related among each other.

CONCLUSION:

This study identified the difficulties arising, if strength diagnostics and evaluation of muscle function are based on complex multi-joint leg extension. Besides a quantitative description of the force-length relation, it was demonstrated by correlations and two examples that neither forces nor joint moments are directly related to one another. According to this, high forces or moments at a certain knee angle don't necessarily imply the same for another knee angle. In

addition, high forces are not implicitly associated with high joint moments, just as above-average joint moments in a certain joint don’t signify the same for the other joints. Based on these results, it’s recommended to do strength measurements in several discipline-specific relevant joint angles, whereas a careful evaluation of muscle function should only be done for great knee flexions due to higher correlation coefficients in this area.
In conclusion, this investigation shows that diagnosis of strength and evaluation of muscle function via external forces must be done with extreme caution.

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